Beyond the Libet Clock: Modality Variants for Agency Measurements

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ABSTRACT
The Sense of Agency (SoA) refers to our capability to control our own actions and influence the world around us. Recent research in HCI has been exploring SoA to provide users an instinctive sense of "I did that" as opposed to "the system did that". However, current agency measurements are limited. The Intentional Binding (IB) paradigm provides an implicit measure of the SoA. However, it is constrained by requiring high visual attention to a "Libet clock" on-screen. In this paper, we extend the timing stimulus through auditory and tactile cues. Our results demonstrate that *audio timing* through voice commands and *haptic timing* through tactile cues on the hand are alternative techniques to measure the SoA using the IB paradigm. They both address limitations of the traditional method (e.g., lack of engagement and visual demand). We discuss how our results can be applied to measure SoA in tasks involving different interactive scenarios common in HCI.

Author Keywords
Sense of Agency; Intentional Binding; Libet clock.

ACM Classification Keywords
H.5.2 User Interfaces: Theory and methods.

INTRODUCTION
The Sense of Agency (SoA) refers to the experience that links our free decisions to their external outcomes, that is, a result of action-effect causality where the match between the intended and actual result of an action produces feeling of controlling the environment [74]. Although the SoA is central in philosophy, psychology and cognitive neuroscience, recent interest of this phenomenon from the field of Human Computer Interaction (HCI), is leading to studies that aim to increase our understanding of how human agency changes with the use of technology [44, 47]. This is due to the concern of exploring user's feeling of being in control (*"I am, who is controlling this"*) in user interfaces [17, 31, 45], and new interaction paradigms that involve touchless interaction [15] and Virtual Reality (VR) [56], i.e., involving gestures, body tracking and mid-air haptic feedback. This research suggests that a system that evokes a low SoA will discourage users from using it, preventing widespread use of the system. However, current agency measurements are limited.

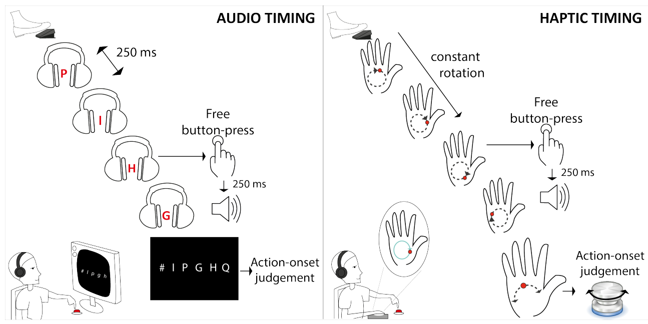

Figure 1. We present alternative timing methods through audio (left) and haptic (right) cues to measure SoA.

On one hand, the most common method is based on explicit and subjective judgment, obtained by simply asking subject whether he/she was the agent of certain action or not (e.g., "did you do that?") [28]. However, research on agency [35, 73] has suggested that explicit human judgement is subject to a number of cognitive biases, as people's decisions are often influenced by unconscious information [60, 71, 78]. This is a limitation in recent application scenarios. For instance, previous studies have provided relevant evidence that cognitive mechanisms of agency taking advantage of body ownership, multisensory synchronous conditions and haptic feedback in VR environments [7, 38, 75]. However, these studies have been limited by subjective methods, i.e., self-reporting questionnaires and scales that are related to subjective judgment of agency.

On the other hand, strategies have been developed to quantitatively measure the SoA; one example is the Intentional Binding (IB) paradigm [27], which indicates a relationship between agency experience and perception of time. While the IB paradigm could provide broader evidence of how people quantitatively perceive causally related events in time (unlike explicit methods), it is based on a very limited timing methodology constrained by requiring high visual attention to a rotating dot around a clock (the Libet clock), which leaves no focus for other visual elements. In emerging interaction paradigms (e.g., VR and on-screen tasks), the Libet clock in its current manifestation cannot fit the visual layout scenario. This

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provides a tension between an experimental task that expands ecological validity and at the same time providing reliable implicit measures.

In this paper, we describe two user studies that extend the IB paradigm by exploring two variations of timing stimuli beyond the Libet clock. Thereby we aim to expand implicit measures of the SoA for more interactive and visual tasks. We propose an Audio Alphabet sequence and a Haptic Clock on the hand as timing stimuli to be used in the IB paradigm (Figure 1). We then compared them with two known timing methods based on visual cues: the traditional Libet clock and a Visual Alphabet on-screen. We hypothesize that by changing the layout of the timing cue but keeping key features (e.g., speed, frequency), an IB effect can still be observed, but reducing current limitations of conventional visual stimuli. Additionally, we assessed user emotion by using our timing methods to evaluate user experience and engagement.

Our results demonstrate that *audio timing* through a sequence of voice (Audio Alphabet) and *haptic timing* through rotating stimulation on the hand (Haptic Clock), measured an IB effect that was not statistically different from that measured with the Libet clock. This suggests our methods as an alternative measure for the SoA using the IB paradigm but addressing current limitations of the traditional method (e.g., visual demand and loss of engagement). We discuss how our work contributes to the emerging research of agency in HCI aiming to advance the understanding of the SoA in the interaction with computers and systems. The main contributions of our paper are thus:

- We introduced alternative timing methods (auditory and haptic) to be used in the IB paradigm.
- We compared and contrasted different layouts of timing stimuli in the IB paradigm.
- We demonstrated that our methods represent more engaging interaction compared with the traditional visual one.
- We discuss applications to measure agency through our methods.

WHY QUANTITATIVE MEASURES MATTER?

Research on agency and decisions [73], has suggested that "explicit measures of the SoA are subject to a number of cognitive biases and are highly sensitive to task demands" [35]. Often the way we think we decide is different from the way the brain actually decides for us. Prior studies have provided evidence of these biases in humans' judgment, by investigating the effect of subliminal primes on people's decisions [13, 67, 68]. Here, people tend to report more SoA when their decisions are actually influenced by external cues than when they resist an influencing prime [78]. Similar effects are observed using *choice blindness*, where people tended to retrospectively invent an experience of their own decision which was clearly not what the brain originally made [32]. Crucially these biases have also been found when comparing qualitative and quantitative measures of agency, suggesting that self-reports and IB may operate differently. For instance, Obhi [72] found that personal reports reflect reduced SoA whilst the quantitative method indicates high IB effect, suggesting that subjective agency and IB do not share a common mechanism.

There exists a salient conflict between explicit and implicit measures of agency, especially when using these methods in VR environments. The IB paradigm mainly consists in simplistic desktop action/outcome tasks (e.g. button-presses and tones), and require to report time using a small stimulus on screen (the Libet clock). This is a challenge in VR environments where users are exposed to visual information constantly and actions are more complex (e.g., full body movements), making difficult to use the IB paradigm in more realistic tasks, preventing thus actual applications. Thereby studies on agency using VR setups are limited to use self-report questionnaires as a measure of the SoA.

An alternative quantitative measure of the SoA is the *interval estimation* method [22] which consists in simply asking subjects to estimate a time interval in milliseconds between and action and its outcome (which is randomly varied). Although this method does not involve significant visual attention, it is less robust as it does not allow distinguish between action and outcome binding in contrast to the IB paradigm [17] (explained in the next section).

THE LIBET CLOCK AND THE IB PARADIGM

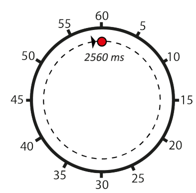

Figure 2. The Libet clock.

In 1982, Benjamin Libet studied the timeline regarding brain neural activity i.e., "Readiness Potential" (RP) and the conscious experience of executing a motor movement. With this end, he proposed the Libet clock (Figure 2), which provides a measure for the subjective awareness of free will "W" (i.e., the time of appearance of the first awareness of wish to act) [43]. It consists of a clock that rotates clockwise once every 2560ms (a speed approximately 25 times as fast compared with a conventional clock). The marked numbers around the perimeter are thus equivalent to about 40ms each. Subjects are asked to report the spatial "clock-position" of a rotating dot at the time when they were first aware of the urge to act (see [42, 57]).

With this method, Libet provided important evidence of origination time of conscious will. He demonstrated that the volitional process (i.e., RP occurrence) arises unconsciously at about 500ms before the actual action; however, the subjective experience of free will (i.e., reported with the clock) emerges 200 ms before the actual motor movement. This suggests that free will does not initiate a voluntary act (which was the original assumption) but it could control performance of the act (i.e., it can veto the act) [42, 65]. Some researchers have suggested that free will could be better described as "free won't" because this process seems to have more to do with the decision to execute an action or not, before the action itself [57]. This finding has changed the traditional view of conscious will, which was though to appear before the RP. However, Libet showed that free will actually follow the onset of RP.

Subsequently, in 2002 Patrick Haggard adapted the Libet clock to be incorporated in the IB paradigm [27]. He used the Libet clock to measure the temporal binding between a voluntary action (button-press) and its sensory outcome (a tone). He demonstrated that actions and outcomes reciprocally attract each other in subjective awareness. As shown in Figure 3(A), subjects exhibit delayed awareness of their causal action (action binding), and early awareness of its consequence (outcome binding), relative to single-event judgment errors. The sum of these two elements (total binding) is thus associated to SoA. The higher the total binding the higher the SoA [22, 52].

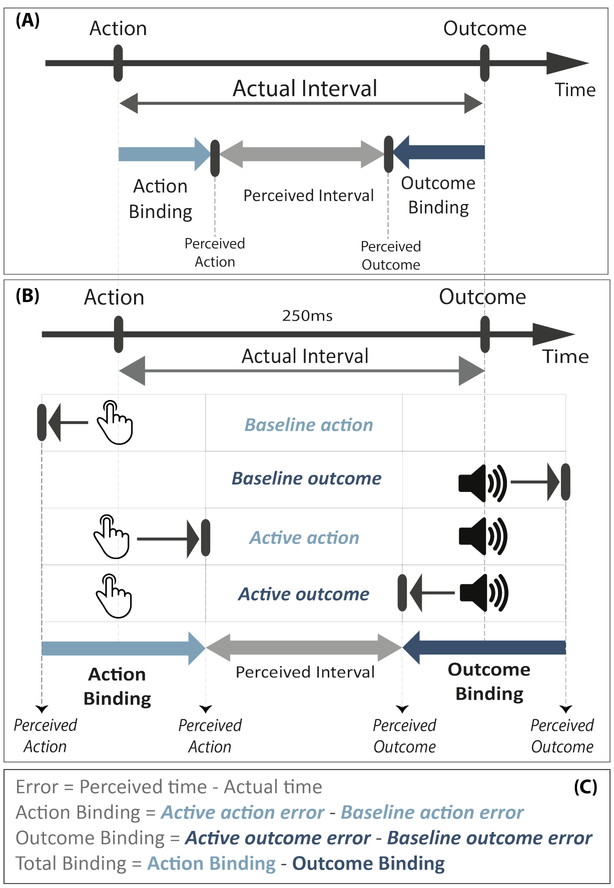

Figure 3. (A) The Intentional Binding (IB) effect. (B) IB conditions and measurement blocks. In baseline conditions, only one vent occurs either action or outcome. In active conditions both action and outcome occur. (C) Formulas to calculate IB relative to single-event judgment errors.

As shown in Figure 3(B), action binding and outcome binding are calculated from two baseline and two active conditions. In the baseline conditions, only one event occurs either action or outcome. In the active conditions, both action and outcome occur. During the task, both actual time (logged by the system) and perceived time (reported by the user using the Libet clock) of the action and outcome are recorded. The errors are calculated by the difference between perceived and actual time. Following this, the Intentional Binding is calculated through the formulas shown in Figure 3 (C).

This temporal binding can be depicted as the bi-directional limitation of Bayesian causal inference [21]: "If two events occur closer together in time, it is more likely they will be perceived as causally related. Therefore, if two events are known to be causally related, they are more likely to occur closer in time" [9, 30]. The IB effect is generally observed when actions are voluntary (e.g., self-paced voluntary keypress); moreover, for involuntary actions (e.g., twitches caused by Transcranial Magnetic Stimulation (TMS)) the opposite effect is observed. Nevertheless, a recent study revealed outcome binding for involuntary actions based on learning and association [35].

The main advantage of the IB paradigm over other methods (e.g., *interval estimation*) is that it provides separate measures of action binding and outcome binding. Having these two measures, gives broader evidence on how system modalities in HCI affect users' SoA. In prior work, Limerick et al. [47] found reduced SoA for speech input reflected in low outcome binding but not in action binding; Cornelio et al. [16] found no differences in action binding for gestural or physical input commands, but found that outcome binding was higher for haptic feedback compared with visual feedback in touchless interaction. Although additional methods are less visual [18, 22], they only give individual time judgment measures, which makes them less informative for HCI research (and wouldn't have helped in the two examples just discussed).

However, although the IB paradigm with the Libet clock has been shown as a robust technique to implicitly measure the SoA [52, 53, 58, 59], this method requires subjects to keep high attention to the Libet clock, which can result monotonous and tedious due to the number of trial repetitions during the IB task (usually 30), producing thus loss of engagement. This prevents more complex setups such as VR environments, thereby alternative methods (but less robust) are used which are related to subjective questionnaires. Therefore, we focused this research to extend the IB paradigm (i.e., a robust technique to measure SoA in HCI) but reducing its high visual demand.

APPLICATION OF AGENCY MEASURES IN HCI AND VR

Recent interest in the SoA from the field of HCI is generating increasing studies that aim to advance the understanding of the role of agency on the use of technology, particularly when using user interfaces. By employing the IB paradigm, these studies have explored the modulation of agency when interacting with new interaction paradigms typical in HCI, i.e., input modalities and system feedback. For instance, it has been demonstrated that skin-based input [29] (tap on the skin) evokes higher SoA in users compared with typical keyboard-based input [17]. This finding may support application in skin-interaction smartwatches [70, 79]. In other hand, speech input has been suggested to diminish SoA [45], which can provide major benefit in interface design. A more recent study showed IB effect in gestural-based input (in-air click gesture) preceding haptic feedback through ultrasound [15], suggesting that mid-air interaction produces SoA in users, even in absence of typical characteristics of touching an object. While these studies have provided relevant evidence of how Intentional Binding operates in HCI, they are still based on simple micro interactions (common in the IB paradigm).

Moreover, prior research has explored agency in more complex actions using self-reports (i.e., explicit judgement). These studies have revealed illusory agency in Immersive Virtual Reality (IVR) using Head Mounted Displays (HMD) [25], suggesting that people may attribute an action to themselves (i.e., illusory agency) even in absence of key aspects of agency experience (i.e., prediction, priming or cause preceding the effect). Here subjects were immersed in VR environments accompanied by visuomotor synchronous conditions to create a strong feeling of body ownership of an avatar seen from the first-person perspective (1PP). Under this immersion, participants self-reported agency of actions performed by the avatar i.e., speaking (assisted by haptic feedback on the thyroid cartilage) when actually not speaking [7]; and walking (assisted by induced visual sway), when actually seated [38].

A large number of studies on agency have suggested that the SoA principally arises due to neural processes that regulate initiation of voluntary motor movement associated to a prior intention to act [26, 51] when reafferent signals (e.g., motor, proprioceptive) match with intention retrospectively [12, 78]. Thus, the intention to initiate a voluntary action preceding a motor movement is key element in producing action attribution. Interestingly, in IVR this does not seem to be crucial to create subjective experiences of agency, as long as the interaction is accompanied by multisensory synchronous conditions common to evoke feeling of body ownership [8, 16, 36].

This generates opportunity to provide user with experiences that are close to those in reality contributing to the quality of interaction (which can have major benefit in VR training simulators for example). IVR has strong potential to produce both psychological and physiological responses by inducing the feeling of body ownership. For instance. changes in body representation [6, 37, 55], changes in interpersonal attitudes [61] or affecting psychological states [19]. There is a huge room for studying agency taking advantages of VR environments.

The role of the SoA in VR becomes more relevant, as in these scenarios, users commonly pose a virtual representation of their own body (avatar) often producing action misattributions (e.g., due to delays or tacking issues). This misattribution may affect the quality of the interaction, especially when such interplay involves touchless interaction (common in VR). Thus, a question rises here, is the SoA quantitatively studied/measured in VR? In a recent study, Kong et al. [39] introduced an Intentional Binding experiment in IVR to investigate if mere observation of a virtual avatar's movements can elicit implicit SoA by inducing the feeling of body ownership. However, their setup is a replica of a desktop IB task (using the traditional Libet clock) which involves a desktop environment preventing actual VR applications. Additionally, the use of the Libet clock might produce divided attention.

Nonetheless their results suggest that VR experience led to a stronger binding effect and that this effect may differ from explicit judgment of agency. However, although this finding opens opportunities to investigate quantitative measures in IVR, it still is constrained by the Libet clock method and its demand of high visual attention.

TIMING STIMULI ADAPTATIONS

The Libet clock appearance and spatiotemporal properties are associated to a typical representation of time measure; aside from its speed, it has the same characteristics than a conventional clock including rotatory cues and numeration. However, the key feature to provide its main function is its particular speed (in order to accommodate time differences in the hundreds of milliseconds). Nonetheless, previous work has adapted the Libet clock by removing the numbers [20, 46] and providing visual cues inside [47, 54] showing no negative effect in the results.

Alexander et al. [3] proposed a modified version of Libet's paradigm to study cognitive decision in contrast to motor decision. They added a steam of letters inside each quadrant of the clock. Participants were asked to choose a letter and indicate the clock position at the moment when the choice was made. Moreover, previous work has completely changed the timing stimuli by using a letter stream on screen without the clock [10, 11, 69]. Here participants are asked to remember the letter that was shown at the moment when they felt the urge to act in a freely paced motor task (button-press). This approach provides advantages of showing unpredictable sequence avoiding common inaccuracies of rotating stimuli [77]. However, these adaptations remain within visual cues on-screen.

Therefore, in this paper, we propose a set of timing stimuli that employ auditory and tactile cues. The aim of this is to address common limitations of visual stimulus, releasing the visual channel and thus direct the visual attention towards other activities. In the next section, we describe two user studies that compared traditional visual timing methods with novel timing methods in an IB task.

STUDY 1. EXPLORING AUDITORY TIMING

In our first study, we investigated the effect of auditory timing stimuli in an IB task. We compared *audio timing* through a sequence of voice (Audio Alphabet), with two know visual timing methods: the traditional Libet clock and a stream of letters on screen (Visual Alphabet). Then we measured IB to explore if a similar effect is observed with *audio timing* compared with visual timing.

Intentional Binding Task Procedure

Every trial started when participants pressed a footswitch and the timing stimulus was presented. Then they were asked to freely press a button (space bar from a keyboard) at elapsed time of their preference (i.e., voluntary action). After an interval of 250ms they perceived a tone (i.e., the action's outcome) which lasted 100ms at 900Hz in frequency. Subsequently after a random interval between 1000ms and 1500ms the timing stimulus stopped and participants were asked to report the cue (visual or auditory) that was presented at the moment when they either executed the action (baseline action and active action blocks) or perceive the tone (baseline outcome and active outcome blocks) as shown in Figure 3(B).

Participants judged their perception of time using three timing methods (Libet clock, Visual Alphabet and Audio Alphabet). For each trial, the judgment error was calculated as the difference between the perceived and actual time. Following this, the Intentional Binding between action and outcome was calculated through the formulas shown in Figure 3(C). Thus, a positive value represented a delayed awareness while a negative value an early awareness. Participants performed 4 blocks (shown in Figure 3B) of 30 trials each in each timing method (3 types), resulting in 360 trials per participant. The full experiment took about 90 min with 2min break between conditions. Figure 4 shows the procedure of a single trial.

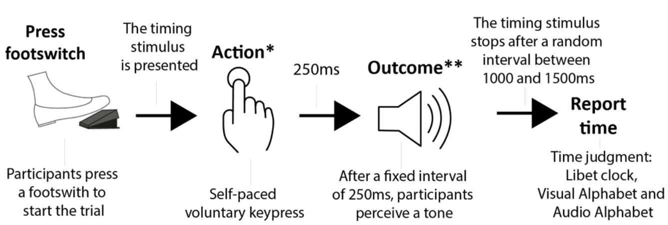

Figure 4. IB task procedure of Study 1 (*not done in baseline outcome blocks, ** not done in baseline action blocks).

Libet Clock method

In the Libet clock method (figure 5 left), participants had to remember the position of a rotating dot around a Libet clock (size 500 pixels) shown on-screen (24 inch, 1920 x 1080 resolution) at the moment of their action/outcome. The clock rotated clockwise once every 2560ms. The numbers of the clock were not used in order to avoid creating visual patterns during the task, instead, after each trial, participants used an external controller (Griffin Powermate Knob Controller) to relocate the dot on the perceived position, as in [15].

Visual Alphabet

The Visual Alphabet timing condition (Figure 5 middle), was similar to that in [10, 11, 69]. Participants were presented an unpredictable stream of consonants on-screen with frequency of 250ms. After each trial, participants were asked to report the letter shown on-screen (24 inch, 1920 x 1080 resolution) at the moment of their action/outcome. Participants were shown a response mapping with five options corresponding to the letter shown during the actual action/outcome (0-back), two letters immediately before (1-back & 2-back) and two letters immediately after (1-forward & 2-forward) [10, 11]. An additional option was given (# symbol) in case that any of the letters shown corresponded to their answer, i.e., the perceived time was larger than 2-back/2-forward.

Audio Alphabet

In the Audio Alphabet timing condition (Figure 5 right), the procedure was similar but differing that the sequence of consonants was presented in form of pre-recorded voice (250 ms in frequency) using headphones in absence of visual cues. The frequency of the voice sequence (same than in Visual Alphabet condition) was determined in a pilot study to identify the speed at which the consonant being said was understandable. After each trial, participants were asked to report the letter they heard at the moment of their action\outcome using a response mapping on-screen as in the Visual Alphabet condition.

Participants wore headphones during all the experiment (including all the timing conditions). In order to explore the uptake of the *audio timing* conditions (as it is different from

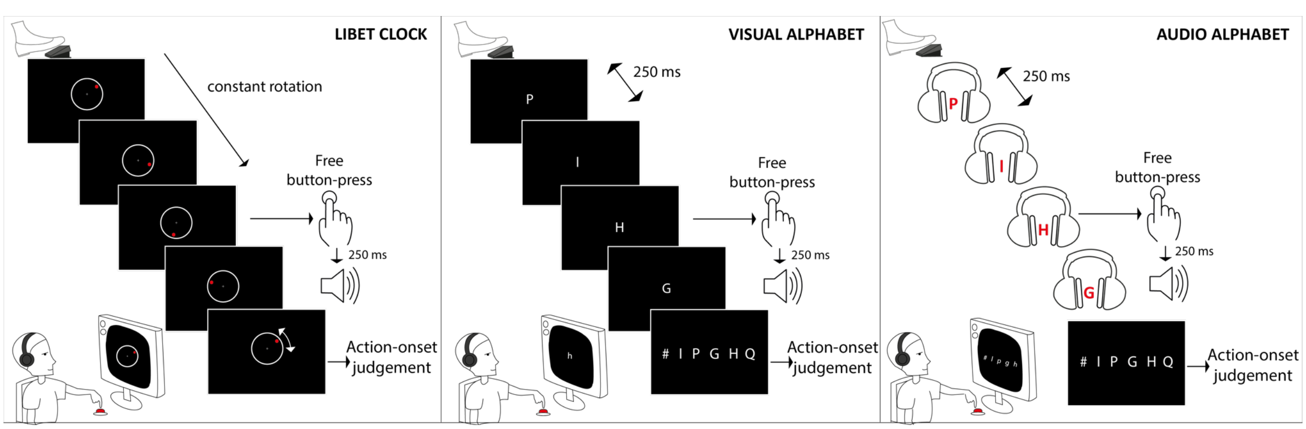

Figure 5. Experimental tasks for the three timing methods: Libet clock (left), Visual Alphabet (middle) and Audio Alphabet (right).

the common visual timing), after each timing type participants were asked to complete a questionnaire to evaluate their emotion by using the three timing methods. They were instructed to report their emotion in that moment but regarding the timing method they used. We employed a PAD scale [48] composed by an 18 bipolar adjective pairs questionnaire [2] (see supplementary material) to measure the three main dimensions of emotions (higher order factors): Pleasure (valence), Arousal and Dominance [62]. These emotional dimensions provided an evaluation of the level of enjoyment and engagement that participants had during the experiment regarding the three timing methods.

Participants
Sixteen right-handed participants (5 female, mean age=28.38 years, SD=4.62) took part in the study. They had normal or corrected-to-normal vision. The local ethics committee approved this study and participants were not paid for their participation. Two participants were excluded because of highly variable time judgement leaving 14 participants for the analysis.

Results
An a priori statistical power analysis was performed for sample size estimation in G*Power, using a repeated measures ANOVA with three timing methods (i.e., Libet clock, Visual Alphabet and Audio Alphabet, repeated 4 times corresponding to the 4 blocks of the IB paradigm). A power of 0.80, an alpha level of 0.05, and a medium effect size (f= 0.25, η_p^2= 0.06) [23] [40], requires a sample size of approximately 12 participants. Thus, our proposed sample of 14 participants was adequate for the main objective of this study.

	Action Binding	Outcome Binding	Total Binding
Libet Clock	29.81 ms (79.5 ms)	-41.79 ms (132.43 ms)	72.59 ms (153.85 ms)
Visual Alphabet	56.73 ms (75.5 ms)	-19.78 ms (100.01 ms)	76.5 ms (143.71ms)
Audio Alphabet	53.75 ms (91.48 ms)	-36.31 ms (57.24 ms)	90.06ms (89.72 ms)

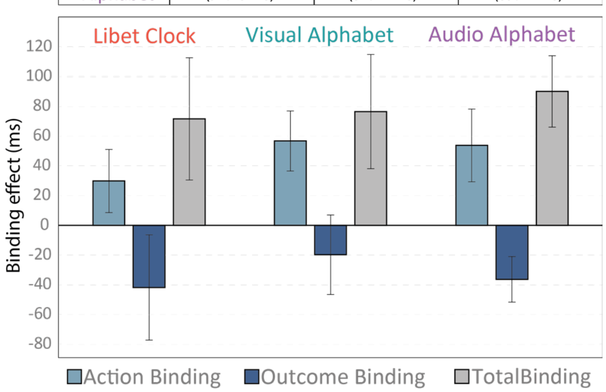

Figure 6. (Top) Average of action, outcome and total binding in milliseconds (with standard deviation in brackets) grouped by timing method. (Bottom) Plot for comparison, a positive value represents a delayed awareness while a negative value an early awareness. Total Binding = Action Binding – Outcome Binding. Error bars represent SEM.

Results on IB
A One-way Repeated Measures ANOVA for each of the binding measures (action, outcome and total binding) was conducted across the three timing methods (i.e., Libet clock, Visual Alphabet and Audio Alphabet). Partial eta squared (η_p^2) is reported as a measure of effect size, according to Cohen [14], we refer to a value of 0.01 as a small effect, 0.06 a medium effect, and 0.14 or greater as a large effect size.

Results showed non-significant effect of the timing methods on the total binding ($F_{(2, 26)}$= 0.271, p= 0.76, η_p^2= .043), similar results are shown for action binding ($F_{(2, 26)}$= 0.490, p= 0.62, η_p^2= 0.13) and outcome binding ($F_{(2, 26)}$= 0.267, p= 0.77, η_p^2= 0.043). We found no significant difference on the binding effects (i.e., action, outcome, and total binding) due to the timing methods used. To additionally explore any potential effect of timing methods on action, outcome and total binding, we performed post-hoc comparisons using Bonferroni correction that showed no statistically significant difference between each timing condition. Details related to mean scores in relation to action, outcome, and total binding in each of the timing methods are presented in Figure 6.

Results on Emotion
A factorial analysis (Principal Components Analysis-PCA, applying a Varimax rotation with Kaiser normalization) was performed to obtain the three dimensions of emotion (Pleasure, Arousal and Dominance) from our PAD scale (see supplementary material). Figure 7 shows the obtained values (normalized) for each dimension.

A One-way Repeated Measure ANOVA for each dimension of emotions (i.e., Pleasure, Dominance, and Arousal) was

	Pleassure	Arousal	Dominance
Libet Clock	0.08 (1.19)	-0.49 (0.91)	-0.58 (1.06)
Visual Alphabet	-0.004 (0.68)	-0.13 (0.84)	0.12 (1.12)
Audio Alphabet	0.06 (0.74)	0.63 (0.81)	0.58 (0.49)

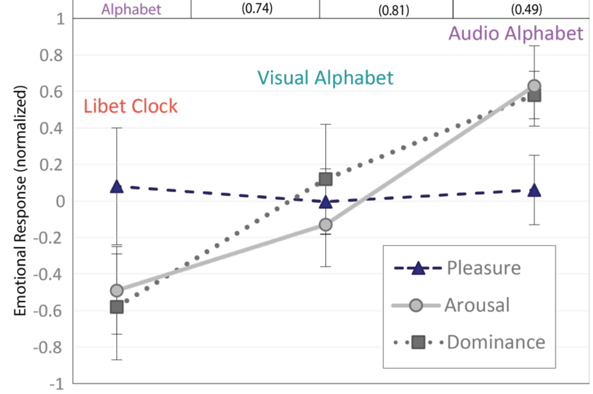

Figure 7. (Top) Average of the emotional responses from participants using the PAD scale grouped by timing method with SD in brackets (values are normalized). (Bottom) Plot for comparison of the three emotional dimensions (Pleasure, Arousal and Dominance) per timing type. Error bars represent SEM.

conducted to compare the effect of the three timing methods on participants' emotions. Results showed a non-significant effect of timing methods on Pleasure (p> 0.5). Conversely significant effects on Dominance ($F_{(2, 26)}$= 8.31, p= 0.002, η_p^2= 0.54) and Arousal ($F_{(2, 26)}$= 9.55 , p= 0.001 , η_p^2= 0.53) are shown. Post-hoc comparisons using Bonferroni correction showed that there is a statistically significant difference in the Dominance dimension between the Libet clock method (M= -0.58, SD= 1.06) compared to the Visual Alphabet (M= 0.12, SD= 1.12, p= 0.02) and Audio Alphabet (M= 0.58, SD= 0.49, p= 0.01) methods. Post-hoc comparisons using Bonferroni correction showed that there is a statistically significant difference in the Arousal dimension between the Libet clock method (M= -0.49, SD= 0.91) compared to the Audio Alphabet method (M= 0.63, SD= 0.81, p= 0.008), and between the Visual Alphabet (M= -0.13, SD= 0.84) and the Audio Alphabet (p= 0.02) methods.

Discussion

Our results show that the IB effect measured with the two traditional methods (i.e., Libet clock and Visual Alphabet) in an IB task consisting of button-press action and tone outcome, did not differ statistically from that measured with the Audio Alphabet. This suggests that participants' time judgement was not modified due to the timing method used (visual or auditory).

The IB values found with the Libet clock and Visual Alphabet methods are in accordance with previous work [10, 11, 15] which confirms validity of our studies. However, by being visually demanding, visual methods are difficult to fit in interfaces and situations in the field if HCI. For instance, studies on illusory agency using VR have been limited by explicit measures (i.e., questionnaires), which are subject to a number of cognitive biases [71, 78]. In this paper, we hypothesized that an IB effect could also be observed using a timing stimulus that does not require relevant visual information, in order to establish a move towards measuring agency in more interactive tasks. Our results provide insights about alternative solutions to employ the IB paradigm in VR applications.

By using auditory timing (i.e., an audio sequence), it could be possible to implicitly measure SoA in tasks involving active conditions, for instance observation of an avatar motion (to evoke the feeling of body ownership) without full attention to a rotating dot. Additional audio sequences could be used, for example pitch although this needs to be further investigated.

Although visual and auditory stimuli have been demonstrated to behave differently in terms of reaction time [24], we found no statistically significant difference in terms of IB effect (i.e., the perceived time interval between a voluntary action and its sensory effect). This suggests that when measuring SoA, *audio timing* could be an alternative timing method in the IB paradigm. For instance, a sequence of voice could be presented to users while manipulating an interface (e.g., menu navigation), thus directing the relevant visual attention towards other activities (e.g., observation of virtual hands on-screen moving and activating buttons).

The duration of the letter shown on-screen in the Visual Alphabet condition was different compared with previous studies, where the duration of visual cue was set as 500ms [69] and 150ms [10, 11]. However, we set the duration for presenting the letters, based on a pilot study to identify the speed at which the consonant being said was understandable (i.e., 250ms) and then stablish the two timing methods involving alphabets (visual and auditory) with same frequency to fairly compare them. In the Audio Alphabet condition, participants visually reported the perceived consonant on-screen for experimental reasons (Figure 5 right), however this can be also done verbally.

The analysis of emotional responses from participants, showed non-significant differences in the three timing methods regarding the pleasure dimension. However, our results suggest that participants felt significantly more aroused and dominant when using the *audio timing* compared with the Libet clock. The IB task usually requires a number of trial repetitions in order to compute average of judgment error (usually 30 trials). This task may be tiring as it is repetitive, which can produce participants' lack of engagement. In our experiment, some of the participants reported that the Libet clock was "boring" and "hypnotizing" and at the end of the task they mentioned felling "sleepy". Our results from the PAD scale reflect this experience as participants reported being significantly more "awake" and "stimulated" while performing the task with the Audio Alphabet. This suggests that *audio timing* could suit better a more interactive task that requires more commitment (e.g., VR) and still being an applicable time measure in the IB paradigm.

STUDY 2. EXPLORING HAPTIC TIMING

In our second study, we introduced a *haptic timing* condition and compared it with visual timing using the typical Libet clock (see Figure 8). In contrast to visual cues to measure time perception, *haptic timing* has not been explored. *Haptic timing* allowed us to measure perception of time based on tactile cues reducing the requirement of visual information. The Libet clock condition was identical to that described in the first study (Figure 9 left). In the *haptic timing* condition (Figure 9 right), the procedure was similar but here the clock was presented in form of rotating haptic stimulation on participants' palm.

Intentional Binding Task Procedure

The procedure for the IB task is identical to that shown in the first study (see Figure 4). Participants heard white noise during all the experiment to block sound from the devices used during the experiment. Participants performed 4 blocks (shown in Figure 3B) of 30 trials each in each timing method (2 types), resulting in 240 trials per participant. The full experiment took about 45 min with 2min break between blocks. Figure 8 shows the procedure of a single trial. Figure 11 shows the experimental setup.

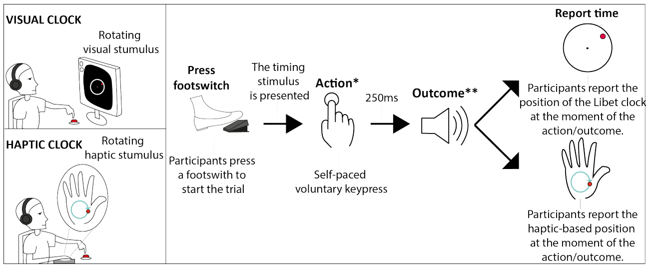

Figure 8. IB task procedure of Study 2 (*not done in baseline outcome blocks, ** not done in baseline action blocks).

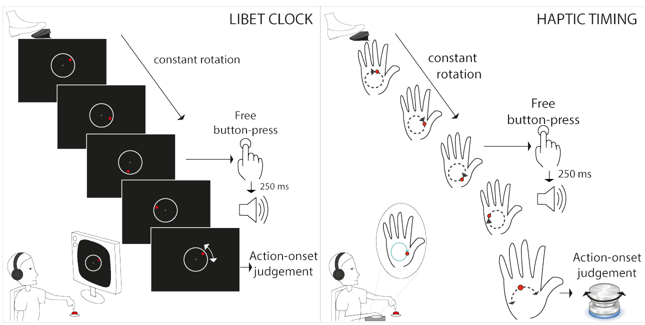

Figure 9. Experimental tasks for the two timing methods: Libet Clock (left) and Haptic Clock (right).

Haptic clock

Before the task started, participants were instructed to place their non-dominant hand (palm-down) on a custom-made box (Figure 10) containing a brush attached to a NEMA-17 Bipolar 48mm Stepper (model 42BYGHW811). The steeper was controlled using an Arduino board and programed to rotate clockwise with same speed than the Libet clock (2560ms per revolution) with a resolution of 3.2ms/step (360°=800steps). The diameter of the rotational circumference was adjusted depending on hand size (normally smaller for female) but was about 6cm. Participants performed the action (button-press) using their dominant hand and the *haptic timing* stimulus was provided on the non-dominant hand. Finally, participants reported the position on the hand where they felt the tactile stimulus at the moment of the action/outcome using an external Griffin Powermate Knob Controller (as in Study 1) to physically relocate the position of the brush on the hand (Fig. 1 right).

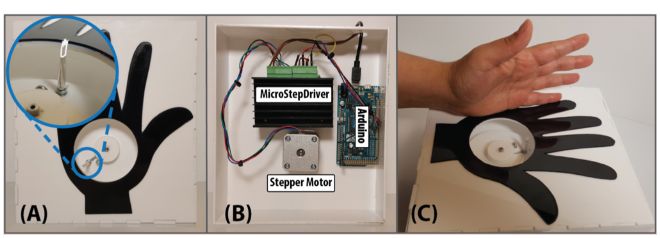

Figure 10. Custom-made box to provide haptic rotational stimulus. 7cm in diameter orifice on top of the box allowed a brush (A) to rotate around participants' palm (C), using a step motor controlled by ab Arduino board and a stepper driver (B).

Participants

Eighteen participants (1 left-handed, 3 female, mean age =28.31 years, SD=5.08) took part in the study. They had normal or corrected-to-normal vision. The local ethics committee approved this study and participants were not paid for their participation. Two participants were excluded because of highly variable time judgement leaving 16 participants for the analysis.

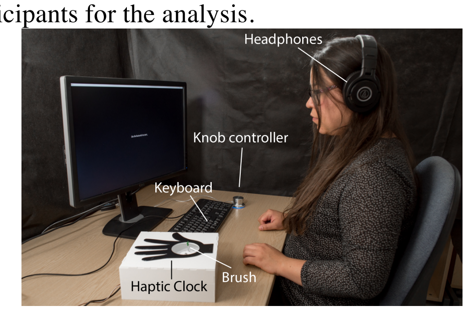

Figure 11. Experimental setup for Study 2.

Results

An a priori statistical power analysis was performed for sample size estimation in G*Power. Running a power analysis on a repeated measures ANOVA with two measurements (Libet clock and Haptic Clock, repeated 4 times corresponding to the 4 traditional blocks of the IB paradigm), a power of 0.80, an alpha level of 0.05, and a medium effect size (f= 0.47, η_p^2= 0.07) [23, 40], requires a sample size of approximately 16 participants. Thus, our proposed sample of 16 participants was adequate for the main objective of this study.

Results on IB

A One-way Repeated Measures ANOVA for each of the binding measures (action, outcome and total binding) was conducted across the two timing methods (i.e., Libet clock and Haptic Clock). Results showed non-significant effect of the timing methods on the total binding ($F_{(1, 13)}$= 0.675, p= 0.18, η_p^2= .014), similar results are shown for action binding ($F_{(1, 13)}$= 1.400, p= 0.25, η_p^2= 0.1) and outcome binding ($F_{(1, 13)}$= 0.356, p= 0.56, η_p^2= 0.027). We found no significant difference on the binding effects (i.e., action, outcome, and total binding) due to the timing methods used. To additionally explore any potential effect of timing methods on action, outcome and total binding, we performed post-hoc comparisons using Bonferroni correction that showed no statistically significant difference between each timing method condition. Details related to mean scores of action, outcome, and total binding in each of the timing method are presented in Figure 12.

Results on Emotion

As in Study 1, a factorial analysis (Principal Components Analysis-PCA, applying a Varimax rotation with Kaiser normalization) was performed to obtain the three dimensions of emotion (Pleasure, Arousal and Dominance) from our PAD scale. Figure 13 shows the obtained values (normalized) for each dimension. A One-way Repeated Measure ANOVA for each dimension of emotions (i.e., Pleasure, Arousal and Dominance) was conducted to compare the effect of the two timing methods (i.e., Libet clock and Haptic Clock) on participants' emotions. Results showed a non-significant effect of timing methods on Pleasure ($p > 0.5$) and Dominance ($p > 0.5$) dimensions. However a significant effect on Arousal ($F_{(1, 12)} = 12.518$, $p = 0.004$, $\eta_p^2 = 0.51$) was observed.

Discussion

Our results showed that the IB effect measured with a Haptic Clock in the form of rotatory timing stimulus on participants' palm was not statistically different from that measured with the traditional Libet clock, both methods in an IB task consisting of button-press action and tone outcome. This suggests that participants' time judgment did not differ due to the timing method used (visual or haptic).

We introduced *haptic timing* stimulus to be used in the IB paradigm to reduce visual information presented to participants. Our results suggest that tactile cues on the hand can be used to measure perception of time as an alternative to visual stimuli. The human hand is highly sensitive due to mechanoreceptive units in the glabrous skin area [33], its resolution ranges from 1mm to 2mm [34]. This property represents a promising tool to judge causally related events in time based on tactile position. In our experiment, participants were able to recognize spatio-temporal stimulation for voluntary action with an overall accuracy of 69 ms, i.e., the judgment error set as the difference between actual and perceive time in baseline active block (where participants reported the action only.)

In contrast to the Audio Alphabet resolution (250ms), the Haptic Clock provides higher resolution as it represents a constant stimulation. Although tactile sensitivity may be affected by sensory habituation (i.e., due to constant tactile stimuli) [64], our participants did not reported feeling habituated to the stimuli. The Haptic Clock condition took about 20min with 4 breaks of 2min between IB conditions (baseline and active). However, habituation may affect sensitivity for longer periods.

While the Haptic Clock also involved rotatory cues as in the visual Libet clock condition, it provides a timing strategy that reduces the visual information for timing stimuli. Furthermore, our results provide insights of exploring *haptic timing* using different and unpredictable patterns. For instance, different shapes, random path trajectories or different body parts (e.g., wrist). However, this needs to be further investigated.

One limitation of the Haptic Clock condition is that participants' hand was placed in a fixed position. Our experimental setup, however was mainly focused on exploring tactile stimulation to measure time perception based on haptic position. Yet, our results provide intuition to provide tactile stimulation using different presentations, for example vibration using wearables gloves or mid-air through ultrasound to avoid user instrumentation.

The analysis of emotional responses from participants, showed non-significant differences in the two timing methods regarding the pleasure and dominance dimensions. However, our results suggest that participants felt significantly more aroused when using the Haptic Clock timing compared with the typical visual Libet clock. Similar to Study 1, participants reported lack of engagement in the Libet clock condition. In contrast, when using the Haptic Clock, they experienced being more "exited" and "stimulated". This suggests that *haptic timing* could be suitable for tasks requiring more engagement.

	Action Binding	Outcome Binding	Total Binding
Libet Clock	23.61 ms (35.24 ms)	-54.56 ms (79.89 ms)	78.17 ms (94.79ms)
Haptic Clock	62.34 ms (118.54ms)	-32.23 ms (143.91 ms)	94.57 ms (142.3ms)

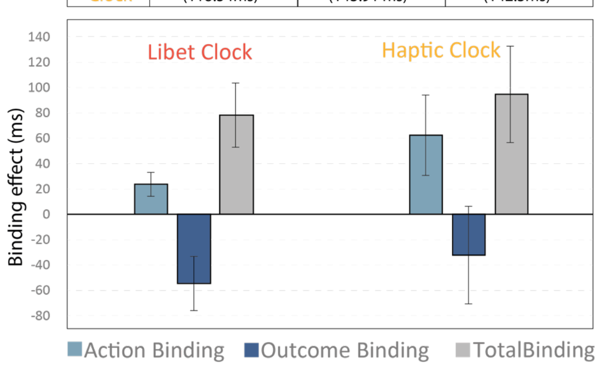

Figure 12. (Top) Average of action, outcome and total binding in milliseconds (with standard deviation in brackets) grouped by timing method. (Bottom) Plot for comparison, a positive value represents a delayed awareness while a negative value an early awareness. Total Binding = Action Binding – Outcome Binding. Error bars represent SEM.

	Pleassure	Arousal	Dominance
Libet Clock	-0.16 (1.29)	-0.6 (0.92)	-0.024 (1.06)
Haptic Clock	0.074 (0.61)	0.62 (0.7)	0.12 (0.95)

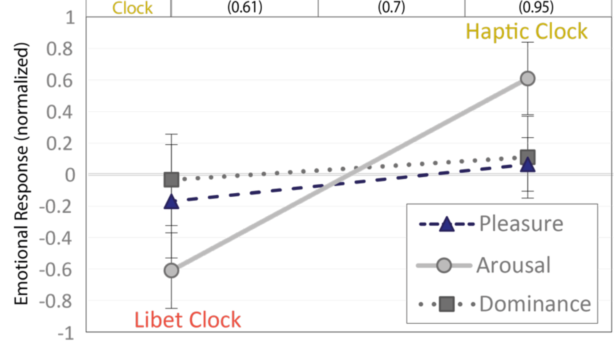

Figure 13. (Top) Average of the emotional responses from participants using the PAD scale grouped by timing method with SD in brackets (values are normalized). (Bottom) Plot for comparison of the three emotional dimensions (Pleasure, Arousal and Dominance) per timing type. Error bars represent SEM.

GENERAL DISCUSSION

In this paper, we introduced *audio* and *haptic timing* to measure SoA using the IB paradigm. Our methods address limitations of current agency measures, in particular that they involve high visual information and are difficult to stay engaged with. Our timing techniques allowed us to measure perception of time through audio commands (Audio Alphabet) and rotating haptic stimulation on the hand (Haptic Clock), in an IB task reducing the required visual cues. The results from two studies comparing our methods with traditional visual timing stimulus (Libet clock and Visual Alphabet) showed non-significant differences in time perception and thus in IB effect. Each timing condition relies on a different modality (i.e., vision, audition or touch) with different cognitive implications. However, those perceptual differences between senses did not significantly bias the IB measurements as shown in our analysis. Yet the absolute difference in the means across timing types shows lower binding for the Libet clock, though this was not found to be significant.

Our results on emotion suggest that timing through audio and touch could provide a more suitable strategy to be used in interactive scenarios. Our participants reported higher arousal and dominance by using the Audio Alphabet and the Haptic Clock. This suggests that our methods not only provided a measure of agency but also improved engagement during the task unlike the traditional Libet clock, which was associated with low arousal dimension.

Previous studies on agency have demonstrated that IB is modulated by affective signals, being higher when a positive emotion is involved compared with a negative emotion [1]. Although the results from the PAD scale showed higher positive dimensions in arousal (not valence) for *audio* and *haptic timing*, this did not influence IB. This is in accordance with [1], where IB was modified by valence dimension only. Yet we used our emotion scale to assess uptake and user experience by using our timing methods instead of assess influence on SoA.

Our work thus opens opportunities to measure agency in active and visual scenarios, expanding the research of the SoA in the field of HCI. We believe that agency implication should be considered in HCI in order to improve instinctive sense of control during the interaction. This is specified in the seventh of Shneiderman's Eight Golden Rules of Interface Design. It indicates that interface design should "*support an internal locus of control*" [66], which refers to the instinctive sense of "I did that" as opposed to "the system did that" [17].

The advantage of extending agency measures is to be able to improve agency in actual HCI applications where user performs voluntary actions i.e., input commands (e.g., gestures [15]) and perceive system feedback (e.g., visual, auditory and haptic), and thus design systems that does not disrupt users' feeling of being in control.

For instance, prior research has shown that visual mismatch due to scaling factors, or retargeting techniques in VR may affect haptic perception [4], feeling of body ownership [41] and virtual presence [63]. These techniques introduce visual conflicts to modify the perceived virtual space [50]. However, the role of the SoA in these scenarios is unknown, and it is unclear if users' SoA during the interaction may be affected by these visual strategies commonly used in VR environments.

The work presented here thus aims to offer alternative variants of timing stimuli in the IB paradigm i.e. a tool that HCI researchers can use and adapt (going through different sensory modalities) in specific applications. The Libet clock method has been widely used and extensively validated, but in situations where the Libet clock does not fit the visual layout (involving relevant visual information), an *audio* or *haptic timing* could be employed.

FUTURE WORK

Based on our results, the follow up work is to carry out an extensive evaluation in actual HCI applications, particularly in VR. Some examples are: *a)* how much visual scaling factors affect user's SoA in navigations techniques [49, 76]; *b)* the effect of virtual presence (induced by scenes visualization) on the sense of personal agency [63]; *c)* to what extent the experience of agency is modified by retargeting techniques [4] without losing significant feeling of control; *d)* how optimization techniques can improve user's sense of controlling a menu system [5] and *e)* measure illusion of agency in more complex displays such as gestural interaction and mid-air haptic feedback (e.g., training simulators or videogames). For instance, we may say that video gamers perceive SoA while interacting with a virtual environment even when they are just observing a virtual representation of their body.

CONCLUSION

Current research on agency in the field of HCI has been limited by agency measures based on subjective judgement. While the IB paradigm provides an implicit and quantitative measurement of the SoA, it has limitations regarding high visual attention. Here we provide two alternative techniques that employ *audio timing* through voice commands and *haptic timing* through tactile stimulation on the hand. Our techniques allow measuring perception of time in an IB task, revealing non-significant differences with the traditional visual method (Libet clock), but addressing high visual demand and lack of engagement. We believe this work will enable agency implication in HCI applications. Measuring users' SoA in broader modalities will allow exploring interaction techniques that give users an instinctive sense of control on the environment.

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